



Jet quenching and γ -jet correlation in high-energy heavy-ion collisions*

Xin-Nian Wang^{a,b}, Yan Zhu^c

^aKey Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

^bNuclear Science Division Mailstop 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94740, USA

^cDepartamento de Física de Partículas and IGFAE, Universidade de Santiago de Compostela, E-15706 Santiago de Compostela, Galicia, Spain

Abstract

Medium modification of γ -tagged jets in high-energy heavy-ion collisions is investigated within a linearized Boltzmann transport model which includes both elastic parton scattering and induced gluon emission. In Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV, a γ -tagged jet is seen to lose 15% of its energy at 0–10% central collisions. Simulations also point to a sizable azimuthal angle broadening of γ -tagged jets at the tail of a distribution which should be measurable when experimental errors are significantly reduced. An enhancement at large $z_{\text{jet}} = p_L/E_{\text{jet}}$ in jet fragmentation function at the Large Hadron Collider (LHC) can be attributed to the dominance of leading particles in the reconstructed jet. A γ -tagged jet fragmentation function is shown to be more sensitive to jet quenching, therefore a better probe of the jet transport parameter.

Keywords: Jet quenching, γ -jet, azimuthal angle correlation, jet fragmentation function

1. Introduction

Strong jet quenching [1] is caused by energy loss of energetic partons traversing through the strongly-interaction medium in high energy heavy-ion collisions. It leads to suppression and p_T broadening of high p_T hadrons and jets in the final states, as well as the modification of γ -jet and dijet correlations in A+A collisions with respect to p+p collisions. The energy loss is the result of multiple scattering and medium induced gluon radiation during the propagation of jets in the medium. In the work presented here, jet quenching and γ -tagged jet modification in heavy-ion collisions at the LHC are studied within a linearized Boltzmann transport (LBT) model [2, 3].

Since photons do not participate in strong interaction, γ -jets are excellent probes for the study of jet quenching without the geometrical trigger bias as in dijet correlations. Jet energy loss and jet structure can be calculated by reconstructing a jet with a jet-finding algorithm. In this study, the anti- k_t algorithm within FASTJET [4] is used. In this presentation, we will first give a brief introduction to the LBT model. By comparing with experimental data, we found a large energy loss for the γ -tagged jets in Pb+Pb collisions at $\sqrt{s} = 2.76$ GeV. We will also examine the azimuthal angle broadening and modification of jet fragmentation functions especially at large and small z_{jet} .

In the LBT model, we assume that all partons propagate along classical trajectories between two adjacent collisions. The scattering center is determined by the probability of scattering, $P_a = 1 - \exp[-\sum_j (\Delta x_j \cdot u) \sum_b \sigma_{ab} \rho_b(x_j)]$ for a parton a , with σ_{ab} the parton scattering cross section and ρ_b the local medium parton density, and the sum over time steps $\Delta t_j = \Delta x_j$ (in natural units) starts from the last scattering point. Each scattering is simulated according to the Boltzmann transport equation, $p_1 \cdot \partial f_1(p_1) = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12 \rightarrow 34}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4)$, where $dp_i = d^3 p_i / [2E_i (2\pi)^3]$, $|M_{12 \rightarrow 34}|^2 = C g^4 (s^2 + \hat{u}^2) / (-\hat{t} + \mu_D^2)^2$ is the square of elastic scattering amplitude in

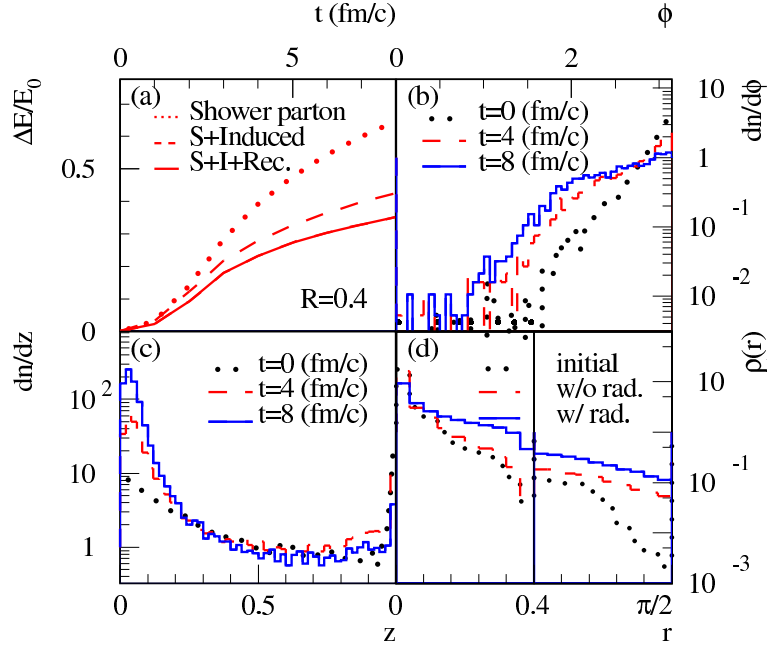


Figure 1. Energy loss as a function of time (a), azimuthal distribution relative to the γ direction (b), jet fragmentation function (c) and jet profile (d) for γ -tagged jets in a uniform gluonic medium.

a small angle approximation with Debye mass μ_D , \hat{s} , \hat{t} , and \hat{u} are Mandelstam variables, $C = 1$ (9/4) is the color factor for quark-gluon (gluon-gluon) scattering, $f_i = 1/(e^{p \cdot u/T} \pm 1)$ ($i = 2, 4$) are parton phase-space distributions in a thermal medium with local temperature T and fluid velocity $u = (1, \vec{v})/\sqrt{1 - \vec{v}^2}$, and $f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i) \delta^3(\vec{x} - \vec{x}_i - \vec{v}_i t)$ ($i = 1, 3$) are the parton phase-space densities before and after scattering. Both shower (p_3) and recoiled medium partons (p_4) after each scattering are followed by further scatterings in the medium. The back reaction in the Boltzmann transport is implemented by transporting the initial thermal partons (p_2), denoted as “negative” partons, according to the Boltzmann equation.

To include induced radiation accompanying each elastic scattering, we using the higher-twist approach[5], $\frac{dN_g^a}{dz dk_\perp^2 dt} = \frac{6\alpha_s P(z)}{\pi k_\perp^4} \frac{p \cdot u}{E} \hat{q}_a \sin^2 \frac{t - t_i}{2\tau_f}$, where $P(z) = [1 + (1 - z)^2]/z$ is the splitting function, $\tau_f = 2Ez(1 - z)/k_\perp^2$ the formation time of the radiated gluon with energy fraction z and transverse momentum k_\perp emitted from a parent parton a with energy E , and $\hat{q}_a = \sum_b \rho_b \int d\hat{t} \hat{q}_\perp^2 d\sigma_{ab}/d\hat{t}$ the jet transport parameter. The Debye screening mass μ_D is used as an infrared cutoff for the gluon’s energy. Multiple gluon emissions induced by a single scattering are assumed to satisfy a Poisson distribution. In the LBT model, all radiated gluons are assumed to be on-shell and their energies and momenta are successively determined from higher-twist approach. Interactions among radiated gluons, shower and recoiled partons are neglected. The strong coupling constant α_s is fixed and will be determined via comparisons to experimental data.

2. Results and Discussions

Within the LBT model, we assume the medium excitation caused by jet-medium interaction to be small, $\delta f \ll f$ and neglect effects that are non-linear in δf . Initial jet shower partons are exported from Hijing [6] by triggering a direct photon from a hard scattering with momentum transfer $q_t \geq 30$ GeV in p+p collisions at $\sqrt{s} = 2.76$ GeV. γ -tagged jets with $p_T^\gamma > 60$ GeV are selected for further propagation in LBT model. Using the anti- k_t algorithm in FASTJET [4], the energy and momentum of a jet is reconstructed by summing up energy and momentum of all shower, radiated partons, and recoiled thermal partons, while subtracting those of negative partons inside the jet cone. It has been verified that there is only a very small difference between jet reconstructed in parton level and hadron level. Jet energy loss is shown in Fig. 1 (a) to increase as the propagation time in a uniform medium with temperature $T = 300$

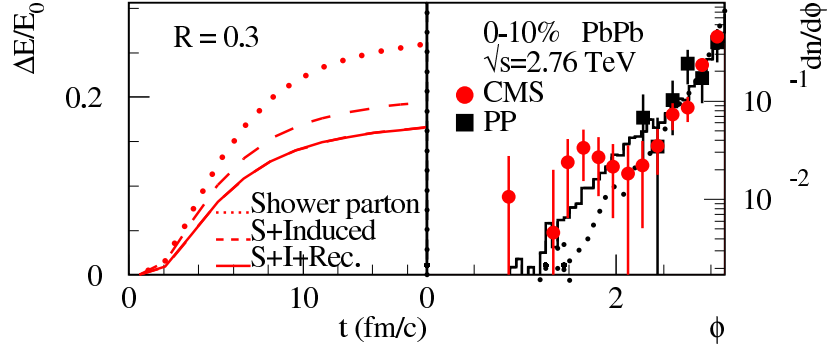


Figure 2. Averaged energy loss as a function of time (left) and azimuthal distribution relative to the γ (right) for γ -tagged jets in central (0%–10%) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV. LBT results are obtained with $\alpha_s = 0.2$ in a 3+1D hydro medium.

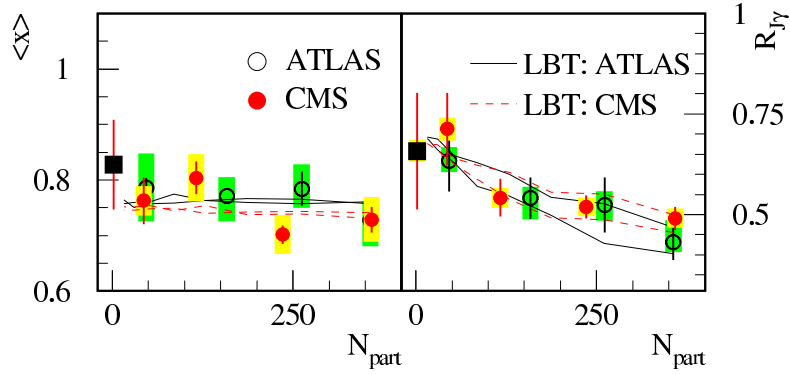


Figure 3. Averaged γ -jet asymmetry $\langle x \rangle = \langle p_T^{\text{jet}}/p_T^\gamma \rangle$ (left) and jet survival rate $R_{J\gamma}$ (right) as functions of the number of participant nucleons in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV from LBT as compared to experimental data [8, 9]. Values of $\alpha_s = 0.15$ –0.23 (dashed line) and 0.2–0.27 (solid line) are used for LBT calculations with CMS and ATLAS cuts, respectively.

MeV and coupling constant $\alpha_s = 0.4$. Radiated gluons and recoiled partons are shown to take part of the jet energy. In Fig. 1 (b), jet quenching is seen to lead to a broadening of γ -jet azimuthal angle distribution with $\phi = |\phi_{\text{jet}} - \phi_\gamma|$. Jet fragmentation function $dn/dz(z = p_L/E_{\text{jet}})$ and jet profile $\rho(r) = \frac{1}{N_{\text{jet}}\Delta r} \sum_{\text{jets}} p_T(r - \Delta r, r + \Delta r)/p_T(0, R)$ are also shown in Fig. 1 (c) and (d). The fragmentation function clearly shows an enhancement at small z while change at intermediate and large z in a uniform medium. Jet transverse profile is broadened in and out of jet cone.

For comparison with experimental data for Pb+Pb collisions at the LHC, we further simulate propagation of γ -tagged jets within LBT in a (3+1)D hydrodynamics [7]. Initial γ -jets from HJUNG are embedded in LBT according to the overlap function of two nuclei with a Wood-Saxon distribution. Different event selections are used according to experimental data from CMS and ATLAS. For CMS data [8], $p_T^\gamma > 60$ GeV, $|\eta^\gamma| < 1.44$, $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 1.6$, and $\Delta\phi = |\phi^{\text{jet}} - \phi^\gamma| > 7\pi/8$, and for ATLAS data [9], $60 < p_T^\gamma < 90$ GeV, $|\eta^\gamma| < 1.3$, $p_T^{\text{jet}} > 25$ GeV, $|\eta^{\text{jet}}| < 2.1$, and $\Delta\phi > 7\pi/8$. In LBT simulations, we use a Debye screening mass $\mu_D^2 = 4\pi\alpha_s T^2$. Fig. 2 shows the average energy loss as a function of time (left), and γ -jet azimuthal angle distribution (right) with $\alpha_s = 0.2$. The energy loss similarly rises initially with time. It however saturates at $t \approx 10$ fm/c because the jet transport parameter $\hat{q}_a = \hat{q}_a^0(\tau_0/\tau)^{1+\alpha}$ with $\alpha \geq 0$ decreases in an expanding medium with time and eventually terminates parton energy loss. The γ -jet azimuthal angle distribution (solid histograms) agrees well with the data (points) as shown in the right panel of Fig. 2. However, a small broadening relative to the p+p (dotted line) result in the large angle is clearly seen, though errors in the data are too big to confirm this. Therefore, more precise experimental measurements will be extremely useful to verify such an expected phenomenon.

In Fig. 3, the averaged γ -jet asymmetry $\langle x \rangle = \langle p_T^{\text{jet}}/p_T^\gamma \rangle$ and jet survival rate $R_{J\gamma}$ are compared with CMS [8] and ATLAS [9] data. The results are consistent with the data when fixed value of $\alpha_s = 0.15$ –0.23 for CMS and 0.2–0.27

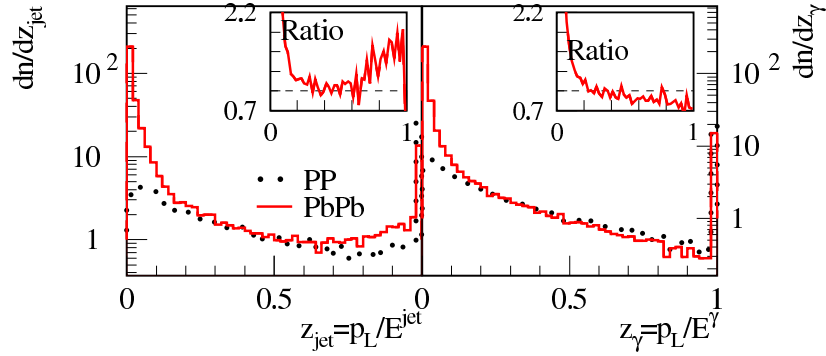


Figure 4. The reconstructed (left) and γ -tagged jet fragmentation functions (right) within a jet cone $R = 0.3$ of γ -tagged jets in central (0%–10%) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV.

for ATLAS is used, respectively. One can see that $\langle x \rangle$ is not quite sensitive to centrality while the jet survival rate is a better observable for measuring the centrality dependence of jet quenching.

Jet fragmentation function at LHC was shown to have an enhancement at both small and large $z_{\text{jet}} = p_L/E_{\text{jet}}$ [10]. This phenomenon can be explained as the dominance of leading particle which takes a large energy fraction of a reconstructed jet. This is verified on the partonic level in Fig. 4. On the left panel, parton distribution function in the fraction of a reconstructed jet energy shows a similar property as the experimental observation. However, as shown in the right panel of Fig. 4, a γ -tagged jet fragmentation function with $z_\gamma = p_L/E_\gamma$ does show an enhancement at small z_γ and a significant reduction at large z_γ , which is more sensitive to jet medium interaction, and is a better probe to extract jet transport parameter.

We have reported jet quenching and γ -jet correlations within a LBT model including multiple elastic scattering and induced radiation in a hot QCD medium. Jet quenching is observed as the energy loss of a reconstructed jet. The LBT results of γ -jet azimuthal angle distribution, γ -jet asymmetry and jet survival rate with fixed α_s agree with CMS and ATLAS data quite well. We observe, however, noticeable broadening in the γ -jet azimuthal angle distribution between Pb+Pb and p+p collisions in the large angle, which unfortunately cannot be discerned by experimental data due to large errors. More precise measurements will be able to verify this non-negligible broadening. The reconstructed jet fragmentation function from LBT exhibits the same behavior as the experimental observation, which shows enhancement at both small and large z_{jet} due to the dominance of leading particle in a reconstructed jet. The γ -tagged jet fragmentation function, however, is shown to be a more sensitive observable for jet quenching for a precise measurement of jet medium interact.

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References

- [1] X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).
- [2] H. Li, F. Liu, G.-L. Ma, X.-N. Wang, and Y. Zhu, Phys. Rev. Lett. **106**, 012301 (2011).
- [3] X.-N. Wang and Y. Zhu, Phys. Rev. Lett. **111**, 062301 (2013).
- [4] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **72**, 1896 (2012).
- [5] X.-N. Wang and X.-F. Guo, Nucl. Phys. A **696**, 788 (2001).
- [6] X.-N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991).
- [7] T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey, and Y. Nara, Phys. Lett. B **636**, 299 (2006).
- [8] CMS Collaboration, Phys. Lett. B **718**, 773 (2012).
- [9] ATLAS Collaboration, Report No. ATLAS-CONF-2012-121.
- [10] CMS Collaboration, Report No. CMS-PAS-HIN-12-013.